Introduction to General Fusion

• Founded in 2002
• Based in Vancouver, Canada
• 75 employees, $100M+ in funding
• Privately backed by investors including Jeff Bezos, Khazanah Nasional Berhad (Malaysian Sovereign Wealth Fund), and the Government of Canada.
• Focused on building a practical, commercially viable fusion power plant
General Fusion Architecture

**FORMATION**
A hot magnetized plasma at 5 million degrees Celsius is formed by a plasma injector and inserted into an approximately three meter diameter compression chamber cavity inside the fusion reactor vessel.

**COMPRESSION**
The inner chamber cavity is formed by a rotating liquid metal, which is quickly pushed inwards by a phased array of several hundred precisely synchronized pistons to symmetrically compress the plasma by factor of 1,000 in volume in several milliseconds.

**HEATING**
Confined within the collapsing metal cavity, the plasma is compressed and heated to over 100 million degrees Celsius, creating fusion conditions.

**FUSION**
Fusion energy is released and subsequently absorbed into the surrounding liquid metal, heating it to about 300 degrees Celsius.
General Fusion Architecture

• Spherical Tokamak Target
• Formed by Coaxial Helicity Injection (CHI)
• Marshall Gun:

Plasma Injector

FORMATION CURRENT IN PLASMA CROSSING GAP
SHAFT CURRENT
INNER ELECTRODE
VACUUM VESSEL
MAGNET COIL
CONNECTION TO COMPRESSION VESSEL

MARAUDER V2  AFRL 1993
Plasma formed by CHI into liquid metal cavity
- Temperature: ~500 eV
- Density: ~1E20 m\(^{-3}\)
- Cavity diameter: ~4 m

Piston array compression
- ~7:1 radial compression
- 20 ms compression time

Liquid Metal Liner serves as:
- First Wall
- Neutron Blanket
- Tritium Breeding
- System Coolant
- Radiation Shielding
General Fusion’s goal

*Commercialize Magnetized Target Fusion*
General Fusion – Some key risks to achieving our goal

**Financing** – Need to Encouraging Investment, Can be challenging when Foundational technologies take a long time to develop with little to show for large amount of effort.

**Insufficient Human resources** - Finding / developing / Recruiting Experts is hard – need credibility in community attract expertise

**Key science risk** – Problems that are not well understood, critical to viability of scheme.

**Engineering risk** – Things that we don’t know how to do yet.
Strategic Development Plan

Engineering solutions

- Address engineering risk – These ARE real risks.
- Tangible First-Of-A-Kind (FOAK) solutions. Technology that is needed to realize goal
- Build corporate know-how
- Shorter, well defined projects
- Demonstrable, understandable milestones that are that are key to investors
- Actual Realization of technology always exposes hidden difficulties. (The devil is often in the details)

Addressing Engineering risk – Things that we don’t know how to do yet.

Helps with financial risk– Demonstrable milestones build investor confidence

Piston Drivers

‘HP150’ - 150kJ -150mm
‘Gun style’ impact driver for liquid metal
Timing performance: < +/- 10 μs
Strategic Development Plan

Building Foundational technologies

- Programs that have low visibility but absolutely necessary for success
- Deliverables are often not very ‘interesting’ to external audience. e.g. Modeling Software often does not have much external value, but is critical to GF’s goal.
- Deliverables take a long time to achieve.
- Building the team

Building Foundational technologies

Supports Development of Key Science – Provide the tools for discovery
Strategic Development Plan

Key Science Development

- Demonstrating viability of General Fusion’s MTF Architecture
- Adding fidelity to project plan
- Publishing Results
- Building company credibility

Progress on Key Science Risk – Problems Critical to viability of scheme.

Helps Build Credibility – Attracts great team, and collaborators - helping address HR risk.

Plasma Target Stability

Experimental Plasma Lifetime improved 70X since 2012

- pi3-083 2-d t(78)=77.003us
- lam (m⁻¹), lamct=0.549028

Plasma Target Stability

- 10,000 microseconds
- 2012-2018-YE
- P3 injector magnetic lifetime Target
- Plasma Target Stability

- 2012
- 2013
- 2014
- 2015
- 2016
- today
- 2018-YE
Strategic Development Plan

Building Community and Collaborations

- Building relationships with Universities
- Open-Source software community
- Academic community at Government / National Labs
- Industrial partners
- Other credible Fusion development efforts, big and small
- Code development partners

Strong Community

Supports key Science effort – Brings expertise, collaboration, and resources to build foundational technologies
Strategic Incremental development

- **De-Risk Engineering**: Cycle of Incremental engineering milestones for physical demonstration of key technologies - helps to encourage funding.

- **De-Risk Key Science**: The cycle, in-turn, facilitates, longer term Key science program.

- **Develop Foundational Technologies**: The cycle further facilitates development of foundational technology that would be hard to fund otherwise.

- **Embraces Rapid Innovation**: “Fail early – Fail fast” ethos.
What does this look like in practice?
Strategic Incremental Development at General Fusion

Program is divided into 3 areas by ~common~ physics:

1. Plasma injectors
2. Compression systems
3. Plasma compression
Lab-scale Plasma Injectors – Progress

• Built on a reduced scale to **reduce iteration time and expense**. Reduced scale allows for fail early – fail fast ethos
• 17 small injectors constructed in last 8 years
• Allow a variety of geometries and magnetic topologies to be explored
• Geometry also used in compression experiments
• Each iteration supported many 1000’s of shots.

30 cm

Magnetic Ring Test (MRT)

PROSPECTOR

Spherical Compact Toroid (SPECTOR)

Plasma Magnetic lifetime

300 us

1400 us

3300 us
Plant scale plasma injectors

- Formation with accelerator - magnetic compression
- Demonstrated magnetic compression & heating of a spheromak: Electron Temperature ~5x during compression

- 2m Ø Direct Formation Spherical tokamak
- 10 MJ pulsed power supply
Plasma Diagnostics – Foundational technology

• Plasma Diagnostics are complex, requiring significant development, and are typical built in-house.

• As the industry develops this is the sort of technology hopefully will become available.

Major plasma Diagnostic systems:
- Magnetic point probes
- Multi-wavelength Interferometers
- Visible light photodiodes
- X-ray spectra
- X-ray imaging
- Visible Spectrometers
- Multi-point Thomson scattering
- Multi-chord FIR Polarimeter
- VUV Spectrometers
- Neutron diagnostics
- Ion dopler (under dev.)
PLASMA COMPRESSION SCIENCE
Plasma Compression - Key Science

Magnetic compression systems
- Large injectors PI1 & PI2

Physical compression systems
- Smaller 300mm Lab scale

- Plasma MHD Modeled Temperature evaluation during compression
- Plasma MHD modeling, and reconstruction, is a significant foundational technology.
Program: Chemical driver compresses an aluminum liner onto a compact toroid plasma

Goals:
• Demonstrate plasma MHD stability in compression (seen during shot: PCS14)
• Demonstrate compression heating (seen during shot: PCS 15)
Compression Systems - Engineering

• 150mm 150kJ Piston system with Servo validated to ±10 µs timing control
• Design is scalable to hundreds of pistons
• Foundational engineering development of high energy real-time servos

Mini-Sphere 1m Ø Liquid metal compression Experiment

• 1 m inner diameter sphere, 14 pistons with servo control, Molten lead loop (100 kg/s)
• Foundational engineering development in liquid metal pumping, seals, shock, materials
Compression Systems – **Key Science** - Instabilities

• CFD Modeling of compression dynamics guides program and build foundational science
• Modeling - understanding Instabilities is key foundational science
• Example:

  **Stabilization of Rayleigh–Taylor Instabilities (RT) with rotation:**

  \[ \ddot{r}_{in} - \omega_{in}^2 r_{in} > 0 \quad \text{RT unstable} \]

  \[ \ddot{r}_{in} - \omega_{in}^2 r_{in} < 0 \quad \text{RT stable} \]

  *Stability Criterion: (Turchi et al. 1976)*
Compression Systems – **Key Science** - Instabilities

- Experimental Program Collaboration with McGill University RT Stabilization in cylindrical compression
- Model Validation

- Rotor Inertia driven colipase – RT stabilized
- Quasi-3D compression
- Model validation
- Foundational science
Bell–Plesset (BP) Instabilities at late time in RT stable regime with high rotation shear.
Collaborative foundational work with McGill University
Experimental Validation for CFD models
Compression Systems – Liquid Lithium – Magnetic field Interactions

• Collaborative foundational work with HyperComp build code to model Lithium free surface and large transient magnetic fields (MHD/CFD)
• Validating code against ‘SLiC’ Experimental campaign - Foundational Technology
Strategic Development - The Parallel Efforts

Engineering solutions

Things that we don’t know how to do yet with tangible milestones.

Foundational Technologies

Programs that have low visibility but absolutely necessary for success.

Key Science

Difficult problems that are not well understood, critical to viability of Architecture.

Addressing The Risks:

Financing – Tangible milestones, encourages Investment

Engineering – required FOAK designs

Difficult to fund infrastructure development that is required for success

Resources – Increasing credibility brings talented people and collaborators

Key science risk – will it work.
General Fusion has demonstrated:

- Magnetic, and chemically-driven compressive heating of plasma
- Plasma lifetimes that, when scaled for size, are sufficient to allow mechanical compression
- Mechanical drivers that have the energy density and timing precision necessary to drive a symmetrical implosion

**Where we are now?**

**What is next?**

Liquid metal plasma compression
Next Step: Integrated Large Scale Prototype

Goals:
Demonstrate, at scale, that fusion relevant temperatures can be achieved using General Fusion’s MTF technology
Validate plasma confinement, stability scaling to high magnetic field, temperature, density

Strategy:
• Optimize performance with flexible operating envelope
• Modularize systems to permit rapid innovation

Key Features and Specifications:
• 3 meter diameter plasma
• 15-25 MJ of plasma formation bank
• Liquid lithium
• 3.5 to 4 ms compression time
• Up to 10:1 radial compression ratio
• 1 compression shot/day operating rate
Next Step: Integrated Large Scale Prototype

Key ongoing development areas:

- Verification of plasma transport as function of scale
- Verifying power density limits in injectors
- Understanding Lithium - plasma interactions in flux conserver
- Development of Lithium compatible piston drivers
- Smooth Cavity formation and compression
- Magnetic field compression with liquid lithium
- Plasma MHD – CFD MHD code development
QUESTIONS?
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